TITLE: Physiological Consequences:
Cardiopulmonary Vestibular, and Sensory Aspects

PHYSIOLOGICAL CONSEQUENCES: CARDIOPULMONARY, VESTIBULAR, AND SENSORY ASPECTS

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SUMMARY

Discussing the physiological consequences of enhanced fighter manoeuvrability (EFM), aspects of cardiopulmonary reactions will be seen during high G manoeuvres, especially the combination of negative G-load followed by high G-onset manoeuvres ("push-pull"). The aicrafts' capability to reach high altitude within a very short time (due to the lift to weight ratio of more than 1) may produce new problems even during normal aircraft operation, e.g. decompression sickness (DCS). The incidence of vestibular problems may be increased by unconventional acceleration exposures. Sensory stimulations may be induced by high acceleration alterations in the roll, pitch, and yaw axis. The support by an advanced G-protection garment will be needed. For the "care free" handling the advanced G-protection device must work without any delay in time even during high acceleration transitions, must secondly include high altitude protection, and thirdly must ensure pilot comfort. Furthermore special training devices are required such as the human centrifuge as a dynamic flight simulator (DFS) with a fully gimballed system, and a spatial (dis)orientation device with a fully three-axes gimballed system. Pilot selection and medical survey with high sophisticated diagnostic tools will become more and more important. Last not least the need of special physical training will be required to enhance the aerobic endurance and the anaerobic power, to train the cardiovascular reflexes, and to increase psychomotoric stability and mental mobility.

INTRODUCTION

In respect of possible physiological consequences superagility includes first of all the aircraft's capability to change its velocity vector in all directions and dimensions in a very short time. This does not only includes new technologies to improve the post stall capability of the aircraft by vectored thrust and electronically flight control system with fast alterations in the roll, pitch and yaw axis, low to medium altitude and low speed. It also concerns the capability of the aircraft to reach high G-loads, high altitude, and supersonic speed.

Physiological consequences may not only occur in the normal operation range of the agile aircraft, but also in extreme edges of the flight envelope and in emergencies. For safe operations with agile aircrafts it will be necessary to consider special procedures in the process of pilot selection, survey, and training. Especially manoeuvring in the post stall regime requires new mental and physical abilities.

Paper presented at the RTO HFM Lecture Series on "Human Consequences of Agile Aircraft", held in Neubiberg, Germany, 20-21 March 2000; Preston, UK, 23-24 March 2000; WPAFB Ohio, USA, 19-20 October 2000, and published in RTO-EN-12.

CARDIOPULMONARY ASPECTS

So far very few pilots have experienced high-agility flight with extreme acceleration stress. Therefore there is very little data in the literature that relate to the effects of G associated with EFM flight. However, it is possible to speculate about the acceleration stress hitting the pilots during enhanced fighter manoeuvrability by transferring the observations from human centrifuge exposures in the dynamic flight simulation mode.

Cardiopulmonary effects during high-agility flight will be induced primary by magnitude, direction, duration, frequency, and onset of acceleration exposure. During high agility flight pilots will experience both impact acceleration with less than 1-second duration and sustained acceleration during manoeuvres that may be completed in several seconds.

To withstand acceleration forces blood pressure has to be increased up to 300 mmHg by the left ventricle of the heart to reach blood pressure at heart level of more than 200 mmHg (figure 1).

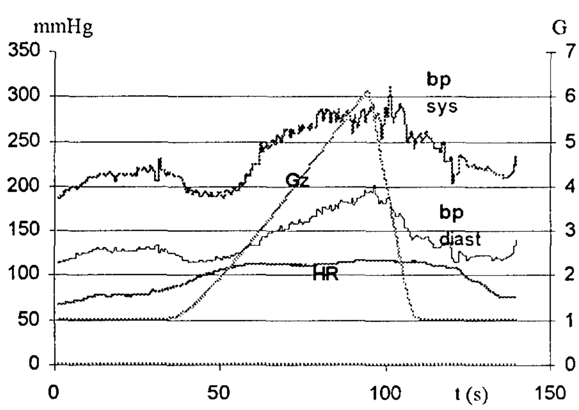

Figure 1: blood pressure (systolic and diastolic) measured by porta pres method during a linear acceleration profile with 0.1 g/s onset up to +6 Gz.

Positive pressure breathing assisted by a breathing regulator or induced by the pilot with active breathing techniques increase the intrapulmonary pressure up to 70-100 mmHg.

There is no doubt that this cardiopulmonary stress – even if the exposure time and frequency is short – demands healthy cardiopulmonary system, confirmed by special medical selection procedures and continuous medical monitoring.

Cardiovascular Aspects of EFM

Despite lower peak Gz levels to be expected during enhanced fighter manoeuvrability, G-induced loss of consciousness (G-LOC) as a result of cardiovascular decompensation during +Gz will become a greater threat. EFM will involve more frequent changes from negative Gz to greater than +1 Gz. Transitions between zero or –Gz and +Gz are known to reduce human +Gz tolerance [1], termed the "push-pull effect" [2]. The decrease of blood pressure and heart rate by vasodilatation during any "push" phase less than +1 Gz will diminish human +Gz tolerance. The Canadian Forces reported that 17% of all G-LOC episodes have been related to push-pull effect, several of them involving F-18 pilots who had been in control of the aircraft [3]. A review of United States Air Force (USAF) accident records determined that F-16s, F-15s and even one A-10 and one T-37 were likely lost because of G-LOC due to push-pull effect.

Increase of ±Gx and ±Gy during enhanced fighter manoeuvrability might not be followed by cardiovascular problems.

Threat of G-LOC

G-induced loss of consciousness will not only be caused by frequent transitions between -Gz and +Gz and the push-pull effect, but will also happen due to the capability of high agility aircraft to reach high +Gz levels within less than 1 second.

Normally there is no risk of G-LOC during accelerations lasting less than 1 second (impact) even with normal G-protection garment and even during push-pull manoeuvres. The cardiovascular system is too slow to react. If the oxygen reserve of the brain is not exhausted by previous high +Gz manoeuvres there will be enough capability to withstand high +Gz acceleration forces of short duration.

Figure 2 shows a push-pull manoeuvre in the interactive steering mode of the German human centrifuge, actively performed by a pilot with conventional anti-G trousers.

This push-pull manoeuvre is executed within 6 seconds. It starts at +1 Gz, reaches –0.5 Gz after 1 second, about another 2 seconds later the peak level of +9 Gz is reached. The duration of the G-level above +8 Gz lasts about 1 second. Finally +1 Gz is reached 2 seconds later again. No G-induced visual impairment like peripheral light loss was reported.

But there is no doubt that G-LOC would have occurred if the G-level of more than +8 Gz would have lasted for more than 1 second.

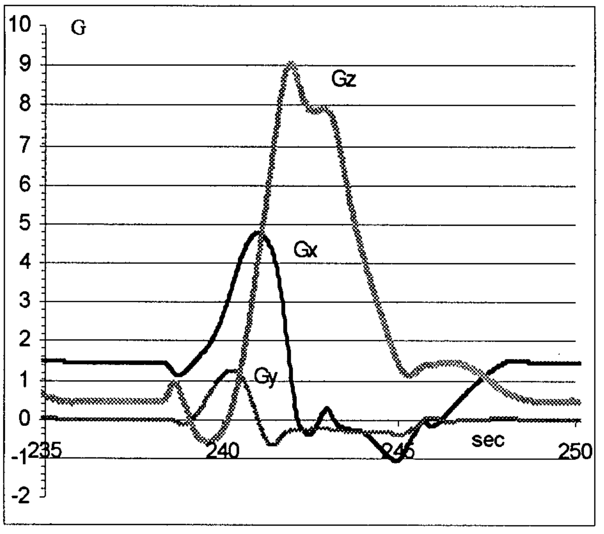

Figure 2: active "flown" push-pull manoeuvre on the dynamic flight simulator (human centrifuge).

Problems with current anti-G suits

Pilots of current EFM-capable aircraft are to wear anti-G suits designed for previous, non-agile aircraft. The original anti-G suit design remains operational today, with minor changes only. Even with an electronically controlled anti-G valve that regulates the flow of pressurised air into inflatable compartments in the G-trousers, the pressure delivery to the trousers requires 1 to 3 seconds to achieve the demanded pressure for cardiovascular protection. The addition of positive-pressure breathing during +Gz (PBG) is a means to decrease fatigue and to enhance the effectiveness of anti-G protection garment. However, currently there is no G-suit that is designed for enhanced fighter manoeuvrability conditions. Even new anti-G valves that will realise rapid and continuous changes in the G-suit pressure in order to adapt to frequent changes of G will have some disadvantages. As the cut-in of the pressure schedule does not cover the total Gz-envelope, a delay will remain between the pressure in the anti-G suit and the immediate change of the pilot's physical state.

Current research in ±Gz protection

For about three years a liquid filled anti-G suit (prototype "Libelle" of *Prospective Concepts AG*, Switzerland) is evaluated in the dynamic flight simulator (human centrifuge) at Koenigsbrueck. With this prototype pilots were able to perform any flight manoeuvre within the limits of +0.9 Gz and +10.4 Gz and a maximum G-onset/offset of ±5 g/s. They could use the HUD, HDD, throttle and stick in order to chase a target-A/C or perform clinical manoeuvres (aerobatics) like in a normal flight simulator or in the real aircraft. The evaluation of the suit was done under clinical and operational conditions, especially during profiles of a simulated A/C with high agility capability and frequent change of acceleration levels from base level up to maximum +Gz. In 34 runs pilots reached G-levels of at least +9 Gz without any arm-pain and with remarkable less fatigue than expected. Simulated air combat manoeuvres (SACM) were performed up to 10 minutes with G-levels up to +10.4 Gz. There was no decrease in situational awareness. Physiological parameters (e. g. ECG) showed no abnormalities.

Prototypes of the new hydrostatic suit "Libelle" demonstrated the ability to help the pilot to perform extreme agile manoeuvres. Excellent anti-G-protection was ensured without time delay during high-G-onset and –offset rates. The avoidance of arm-pain was the most impressive result. Even as there is a wide individual spread in the reached G-levels during the passive acceleration profiles evaluation (due to "learning effects" and perhaps not exact custom fit), the operational benefit of the prototypes was convincing.

Need for research and training

Up to now there is only little information about physical demands imposed by high-agility flight. Understanding these complex translational, rotational, and gyroscopic phenomena requires reassessment of well-established concepts. While some speculation has occurred on the effects of G in high-agility flight, this is mostly based on gradual or rapid G-onset studies which are not representative for high-agility accelerations. The human physiology will be the limiting factor in high-agility flight. Pilot's G-tolerance in this environment will be limited by G-LOC mishaps, visual problems, and vestibular illusions.

Acquiring and understanding of human factors in enhanced fighter manoeuvrability flight will be central topic in future. Validated laboratory tools and proven experimental methods are needed as well as acceleration devices capable of ±Gz, ±Gy, and ±Gx. These modern human centrifuges should be able to simulate the acceleration profiles of enhanced fighter manoeuvrability. The capability of reliable transitions between -Gz and +Gz, active powered gimbals to reach angular velocities of at least 10 rad/s², and acceleration onsets of more than 10 g/s will be the technical requirements to understand the human physiology in the envelope of forth generation aircraft and to optimise crew protection systems.

France, Sweden, and Great Britain undertook great effort to construct new advanced human centrifuges.

Today the German Air Force is planning to upgrade its human centrifuge to meet the specified requirements.

Furthermore, physical fitness training and education must have high priority for Eurofighter "Typhoon" (EF) aircrew. Training facilities should be collocated with EF squadron accommodation. Aerobic endurance, anaerobic strength, and the capability of co-ordination is a must for efficient anti-G protection.

Cardiopulmonary effects of decompression bubbles

Raising the ceiling of current flight operations will lead to an increase in altitude exposure hazard and consequent incidence of decompression sickness (DCS) symptoms. Agile aircraft like the F-22 and the EF are capable to reach a flight altitude up to 60,000 ft with a climb rate of 50,000 ft/min. With the current cockpit pressurisation schedule there is more than a theoretical chance for the pilot to be hit by decompression sickness, when wearing the common aircrew equipment [4, 5].

A pressure altitude of 21,500 ft seems to be the critical threshold where the incidence of DCS increases rapidly and the chance to experience decompression sickness symptoms is greater than 50%. With the normal cockpit pressurisation schedule the critical cockpit pressure altitude of 21,500 ft will be reached at FL 480 (48,000 ft flight altitude).

Using of 100% oxygen is necessary to provide additional protection. It is highly recommended that the cabin pressure differential should be increased to at least 6 PSI instead of current 5 PSI. For escape or in case of rapid decompression in a flight altitude above 50,000 ft the pilot has to be equipped with a (partial)pressure suit. There is no doubt, that a partial or even a full pressure suit will decrease pilot's mobility and comfort. New concepts for protective garment have to be developed.

Venous gas emboli (VGE) and DCS

Bubbles are routinely detected in the venous blood (venous gas emboli) after decompression at altitudes above 12,000 ft. As the more common occurrence of decompression sickness relates to limb pain (bends), cardiovascular effects of decompression bubbles should be discussed. The scope and the magnitude of the problem are proportional related to the gradient of decompression (pressure/time relationship) and hence the amount of gas bubble formation. Not only after rapid decompression, but also during ascend in a altitude chamber with a climb rate of 4,000 ft/min bubble formation can be detected. Knowing this it is to be assumed that gas bubbles formation will occur during high performance take-off or rapid cabin pressure changes during maximum climb rate manoeuvres in an air combat scenario.

The cardiovascular effects of decompression bubbles are presented by symptoms ranging from local blood flow abnormalities, due to mechanical blockage of minor blood vessels, to complex neural effects or complete circulatory collapse.

Intrapulmonary shunts and PFO

Normally the pulmonary microcirculation in the lungs is the filtering mechanism of the bubbles. No bubbles can reach the left ventricle of the heart, no bubbles become arterial gas emboli (AGE). The condition whereby venous bubbles cross pulmonary capillaries might be pulmonary hypertension – induced by anti-G breathing techniques or positive pressure breathing during G-load (PBG) or in high altitude (PBA). In addition to that, pulmonary hypertension might open extra-alveolar arteriovenous shunts, allowing VGE to spill over and to become AGE [in 4].

The prevalence for a patent foramen ovale (PFO) is 20-30% in the human population [in 4]. A PFO is essential for fetal life since it allows blood to pass from the right heart to the left heart in order to bypass the collapsed fetal lungs. Usually within the first year of life this foramen will be closed. Even if there is no anatomical closure by fibrous adhesions the foramen is usually functionally closed because the pressure in the left atrium of the heart is generally higher than in the right atrium.

Venous gas emboli induced by altitude decompression may pass the PFO even in normal pressure environments. The functionally atrial right-to-left shunt allows the gas emboli to cross over when rapid and substantial venous flow to the right heart occurs. Typical situations are:

- G-offset
- Cessation of positive pressure breathing,
- Cessation of the L-1 or M-1 anti-G straining manoeuvre
- Valsalva manoeuvre
- Coughing.

With the new envelope of modern agile fighters the exposure of the pilot to extreme physiological stress is not only likely but probable. Exposure to extreme low pressure without the benefit of denitrogenisation or full protective coverage is likely to be capable of producing silent or overt decompression sickness symptoms. Exposure to assisted positive pressure breathing (PPB) in excess of 60 mmHg in a population likely hiding a 25% incidence of PFO may produce right-to-left atrial shunting as a consequence.

One consequence is discussed and it is recommended that an extension of the echocardiographic examination will be introduced at pilot selection for fourth generation aircraft. The German Air Force Institute of Aviation Medicine has already established the transoesophageal echocardiography for the medical examination of EF pilot. Candidates.

VESTIBULAR AND SENSORY ASPECTS

Discussing the sensory consequences of enhanced fighter manoeuvrability, the ability to execute manoeuvres in the post-stall regime, with controlled side slip (lateral acceleration) and with high angle of attack (AOA) far beyond the maximum lift and aerodynamic limits is most relevant. This "supermanoeuvrability" is enabled by thrust vector control, aerodynamic design, fly-by-wire flight control system, and a thrust-to-weight ratio exceeding 1.

The human complex stress envelope in supermanoeuvrable flight is discussed controversial. In the post-stall regime it is expected that maximum +Gz will be less than in current aircraft, but 0 or –Gz will be much more frequent due to negative AOA in the energy recovery phase. However, agile flight includes also high speed turns like defensive or avoidance manoeuvres even during supersonic speed. Positive accelerations peak levels up to +15 Gz and in the negative Gz-regime up to –10 Gz have to be expected. Although of a very short duration, high G-onset, G-offset and possible G-transition between negative and positive G-load (push-pull manoeuvres) will have to be faced. In addition to the cardiovascular effects sensory and vestibular symptoms will increase and may become the limiting factor during agile flight.

Albery [6] estimated that maximum Gx values are within the limits of ±6.5 G with a maximum G-onset and G-offset of ±5 g/s. The yaw authority may increase lateral accelerations during agile flight up to ±4 Gy with the maximum G-onset and G-offset of ±2 g/s. X-31 test flight results however showed nearly no ±Gy acceleration forces. Lateral G's decrease the pilot's handling capability. To avoid this, these "yaw-looking" manoeuvres were flown by high roll rates (up to 240°/s) with high AOA. Nevertheless when initiating the roll input impact-like Gy's due to the high angular acceleration can't be avoided.

The linear acceleration transitions and the high angular accelerations (pitch: ± 180°/s, roll: ± 360°/s, yaw: ± 90°/s) with extremely high onsets and offsets may increase vestibular disturbance and possible spatial disorientation.

Consequences of supermanoeuvring for semi-circular canals and otoliths

The magnitudes of angular accelerations as provided by Albery [6] are not beyond the normal sensory function of the semicircular canals. One may even expect that the canal responses as for instance during the Cobra- or the Herbst-manoeuvre, will rather accurately reflect the actual angular motion, because of the fast rotations over a limited angle. Simply said, acceleration will deviate the cupula, and the deceleration will erect the cupula back in the original position. This happens faster than the 2nd-order canal characteristics are able to neutralise the response during the rotation. This implies that most of the time the nystagmic response will be adequate as well during post-stall manoeuvring. However, linear accelerations in supermanoeuvring aircraft are most probably different to those of conventional aircraft as they affect the pilot from all directions. Moreover, the magnitude of the acceleration vector will vary, but will be most of the time exceeding 1G, perhaps up to 4G during post-stall manoeuvring. In that case, the gain of the canal response in terms of nystagmus or in terms of motion perception may be different from the optimum response at 1G. Evidence for these interactions is available from parabolic flight experiments.

The G-loads encountered will not destroy the otolith system, as the G-loads in the post-stall regime will be smaller than pulled in conventional high-performance aircraft. On the other hand, G-loads > 3G will generate nystagmus which will be inadequate given the situation [7].

It is also of interest that the intersubjective variability in the magnitude of this nystagmus is considerable, as is the capability to suppress the nystagmus by visual fixation. There is not much known about the horizontal nystagmus following stimulation along the Gy axis, because of unpleasant attitude for subjects in conditions of Gy > 2G. This would require further research.

For a more detailed analysis of the perceptual consequences of the sensory system involved, the combined recordings in linear and angular encountered accelerations should be available for model simulation.

Subjective vertical and spatial orientation

The central vestibular system will have problems in accurately interpreting the otolith input if it concerns a sustained G-load. Present motion perception concepts believe in low pass filtering of the otolith output to preserve gravity, while the canal response is also involved in the internal reconstruction process of the gravity vector, the subjective vertical. In view of increased G-load and its changing directions - even without a detailed analysis - it is obvious that this will

result in a subjective vertical that does not correspond to the gravity vector.

For current spatial orientation, the system has to relay on the visual information. According to the present models on visual-vestibular interactions, the post-stall manoeuvring should not pose insolvable problems to the data processing of the sensory systems involved in maintaining spatial orientation. But this is only true as long as there is ample vision position and motion information available. This is in accordance to the verbal reports of the test pilots.

It is feasible that the movement of the aircraft as such is more provocative for the vestibular data handling when the head is fixed to the head rest compared to the pilots in air-to-air combat manoeuvring trying to keep their gaze and consequently their head fixed on the adversary. In this case the angular motion of the head is much more natural than the motion of the aircraft, and therefore more easily and accurately to handle.

Although one would imagine that a high AOA causes a difficult perception of the flightpath, X-31 pilots consider it to be no problem in visual air combat, because the target is used as the reference.

Pilot reports

No additional human factors or physiological limitations were encountered on X-31, after flying the F-16 or F-18, even the F-4 aircraft. Disorientation was not encountered. But all X-31missions were flown in daylight, in visual meteorological conditions (VMC), with excellent sight and good horizon. And all the missions were flown after hours and hours in the flight simulator.

One single episode, spiralling down into and through a cloud layer, suggested that poor weather, poor visibility with no horizon, intermittent instrumental meteorological conditions (IMC), few cues and alternating „head down“ conditions could pose problems. „Head inside“ was not enjoyed. „Care free“ handling and manoeuvring is important in all fighter aircraft. It allows full attention to be paid to the adversary and the tactical situation: full situational awareness without the distraction in the melee one's own aircraft may depart its own control envelope.

X-31 flight control system (FCS) was set up to provide post-stall manoeuvring with zero side slip. This gave little Gy and very comfortable manoeuvring.

The reports of the pilots were encouraging in view of the predicted problems due to the complex sensory stimulation. However, it might be that clear visibility is a prerequisite for this achievement. Therefore it was assumed that at least the adversary as a referent point - even as a virtually picture in the primary flight instrument - must be integrated into the leading sense, the vision, to avoid spatial disorientation in VMC.

Research tools

Because of the G-loads applied to the pilot from different directions, a research tool with centrifuge capabilities and a fully gimballed system is required, as well as full visual displays. Dependent on the particular goal of the research, choices can be made between several systems available (Table 1). Another brand new system, located in the Netherlands, seems to be capable to do research in this area. It is a fully three-axis gimballed system with visual displays, called "Desdemona". It also allows heave over 2 meters, and may displace itself along a 8 meter track, which is placed on a rotator, allowing centrifugal forces up to 3G.

Vision and vestibular illusions

Pilots rely on flight instruments as their primary defence against visual and vestibular illusions and loss of situational awareness. The various head up display (HUD) designs, attitude indicators (AI), and associated primary flight instruments allow the pilot to determine spatial orientation relative to the earth in degraded visibility. Translational and rotational accelerations are known to affect spatial orientation through induced vestibular and proprioceptive illusions. Loss of spatial orientation can lead to loss of situational awareness.

Current AI/HUDs display a two dimensional depiction of the aircraft attitude relative to the horizon. Neither instrument effectively displays the yaw or the velocity vector. Most airspeed indicators are pneumatically driven and become unreliable below the stall-speed. Thus, the pilot of an EFM-capable aircraft, flying at high-AOA during post stall manoeuvring, employing current flight instrument displays, would receive inadequate orientation and velocity information. A HUD design in the X-31 depicting the velocity vector has proven confusing. Vestibular illusions, not yet identified, will lead to pilot misperceptions of flight orientations that may be difficult to counter with existing instrument displays. Improved instrumentation will be needed to counter the severe vestibular illusions that will certainly be associated with enhanced fighter manoeuvrability especially in poor weather conditions.

Off-boresight targeting may pose problems in terms of a second visual frame reference, which will affect the situational awareness of the own aircraft. Since this depends also on the visual information, off-boresight targeting may easily lead to disorientation. Weather specific symbology in the HUD or the helmet mounted displays (HMD) will enable the pilot to remain fully aware of his situation, remains to be investigated.

Vestibular illusions

Spatial orientation of pilots will be especially challenged by lateral (Gy) and longitudinal (Gx) accelerations that will be experienced during angular accelerations and high AOA. High agility fighter pilots will experience lateral G in combination with long radius angular acceleration. The effects of this combination are considerable unknown and will likely be associated with currently unidentified vestibular illusions. While the natural tendency of any pilot might be to reposition the head in the direction of rotation , preoccupation with tactics may not allow orienting compensating movements. Thus, there will be a large combination of possible disorienting stimuli. The speed of rotation in EFM-capable fighter aircraft may be significantly greater than that seen previously, and may be combined with other acceleration stress. Head movements during yaw manoeuvres may provoke disorientation and motion sickness.

Several important illusions in non-agile aircraft were identified only after loss of aircraft. A notable example being the somatogravic illusion which occurs during aircraft carrier take-off or rapid acceleration in fighter aircraft. Spatial orientation can be expected to be a serious limitation in EFM-capable fighter aircraft.

Motion sickness

As discussed above, based on the vestibular information the vertical will differ in magnitude and in direction from the gravity vector. Current motion sickness modelling is based on the concept that the main conflict causing motion sickness is the difference between the vertical as determined from the sensory inputs and the vertical as determined on the basis of previous motion information. Beside this sensory caused mismatch situation the misperception from sensory cues and delayed visual cues, independent from the vertical, may cause motion sickness, like simulator sickness.

In view of the fast manoeuvring it is unlikely that the internal model of "passenger" can keep up with the sensory side, giving sufficient conflict to provoke motion sickness. Since expectancy plays a large roll in motion perception, and the pilot is in control of the manoeuvres, this will enable the internal model of the pilot to keep up with the sensory side. More-over, as indicated by the pilot reports, the sorties flown so far were in good visual conditions, allowing the visual system to correct for the vestibular insufficiencies in determining the vertical. These two factors should reduce the chance on motion sickness considerably.

In view of the above one should avoid conflicting frames of reference, for instance symbology on the HUD in the helmet (HMD) should be consistent during head movements. In general, dissociation between the reference frames of the head, helmet, display and airframe should be avoided. Although motion sickness may be encountered in conventional aircraft, supermanoeuvring is thought to have an even more provocative character. Extensive training and gradual acquaintance with this type of manoeuvres should be considered using (dis)orientation trainers, advanced centrifuges (Table 1), inverted time (ground: gyro-wheel, triplex, somersault- swing, and in the air), aerobatics in aerobatic aircraft.

Countermeasures

Spatial Disorientation (SD) in superagile aircraft is a threat which is not different from the threat in conventional aircraft. Just as in normal aircraft, spatial disorientation is threat because it may occur unexpectedly. This applies also to the superagile aircraft when they are not engaged in supermanoeuvring. During supermanoeuvring a Type 1 (unrecognised) SD is highly unlikely to occur, but Type 2 (recognised) can occur easily in bad viewing conditions. Also it will be recognised easily, it may be difficult to recover, because of the dissociation between the velocity vector of the aircraft and the aircraft attitude.
It is obvious that normal procedure training and training of additional skills (such as recovery from Type 2 SD) is required.

Several of the items discussed above are at present time under investigation. A survey of the relevant items to be studied for supermanoeuvrable aircraft handling is useful, as is joined research since the research tools are expensive and therefore scarce.

Until more ground based research has been done on the effects of superagile manoeuvring on motion sickness provocation, one should restrict conversion to superagile aircraft to those pilots who have a history free of motion sickness.

Demonstrations and training of supermanoeuvres in ground based devices give responses similar to what is encountered in the air. Otherwise an internal model will be build up which does not correspond to the real situation. Since the real conditions may cause motion sickness as well, one should carefully differentiate between motion sickness and simulator sickness in the ground based devices. One should be aware that G-seats are of limited value in supermanoeuvring aircraft simulators because of the G-load coming from other directions than the pilot's z-direction.

Tactile cueing and 3D-audio could be tools that are helpful in maintaining spatial orientation during supermanoeuvring, and therefore help to prevent motion sickness. Whether this is true indeed, requires a considerable research effort.

SUPERMANEUVERABILITY SIMULATOR MATRIX (GROUNDBASED)

FACILITY	TYPE DEVICE	NUMBER OF X, Y, Z AXES SIMULATED	MAX G ONSET	VISUAL DISPLAY	RATING
DES (WPAFB)	Gimballed Centrifuge	Two	20 G (1 G/s)	120° x 60°	Good-7
DFS (VEDA)	Gimballed Centrifuge	Two	40 G (13 G/s)	90° x 30°	Excellent-9
GAF IAM (Koenigsbrueck, Germany)	Gimballed Centrifuge	Two	12 G (5 G/s)	24° x 32°	Good-8
Singapore AF	Gimballed Centrifuge	Two	15 G (6 G/s)		Good-7
US Navy (Lemoore NAS)	Gimballed Centrifuge	Two	15 G (6 G/s)		Good-7
LAMARS (WPAFB)	5 DOF Flight Simulator	Three	(1.6 G/s)	266° x 108°	Good-5

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